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A high-significance detection of non-Gaussianity in the WMAP 5-year data using directional spherical wavelets

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ABSTRACT
We repeat the directional spherical real Morlet wavelet analysis, used to detect non-Gaussianity in the Wilkinson Microwave Anisotropy Probe (WMAP) 1-year and 3-year data (McEwen et al. 2005, 2006a), on the WMAP 5-year data. The non-Gaussian signal detected previously is present in the 5-year data at a slightly increased statistical significance of approximately 99%. Localised regions that contribute most strongly to the non-Gaussian signal are found to be very similar to those detected in the previous releases of the WMAP data. When the localised regions detected in the 5-year data are excluded from the analysis the non-Gaussian signal is eliminated.

Key words: cosmic microwave background – methods: data analysis – methods: numerical

1 INTRODUCTION

The statistics of the primordial fluctuations provide a useful mechanism for distinguishing between various scenarios of the early Universe, such as various models of inflation. Furthermore, the primordial fluctuations give rise to the anisotropies of the cosmic microwave background (CMB), which may be observed directly. In the simplest inflationary scenarios, primordial perturbations seed Gaussian temperature fluctuations in the CMB that are statistically isotropic over the sky. However, this is not the case for non-standard inflationary models or alternative models to inflation. Evidence of primordial non-Gaussianity in the CMB temperature anisotropies would therefore have profound implications for the standard cosmological model.

Initial analyses of the Wilkinson Microwave Anisotropy Probe (WMAP) 1-year (Bennett et al. 2003), three-year (Hinshaw et al. 2007) and five-year (Hinshaw et al. 2008) observations of the CMB (hereafter referred to as WMAP1, WMAP3 and WMAP5), performed by Komatsu et al. (2003), Spergel et al. (2007) and Komatsu et al. (2008) respectively, find no evidence for deviations from Gaussianity. However, no one statistic is sensitive to all possible forms of non-Gaussianity that may exist in the WMAP data due to either foreground contamination, systematics or of primordial origin. It is therefore important to test the data for deviations from Gaussianity using a range of different methods and, indeed, many additional studies have been performed on the WMAP1 and WMAP3 data: Bernui et al. 2007; Cabella et al. 2005; Cayón et al. 2005; Chen & Szapudi 2005; Chiang et al. 2003; Chiang & Naselsky 2006; Chiang et al. 2007; Coles et al. 2004; Colley & Gott III 2003; Creminelli et al. 2007; Cruz et al. 2005, 2006, 2007; Dineen et al. 2005; Eriksen et al. 2004, 2005; Eriksen et al. 2007; Gaztanaga & Wagg 2003; Gott et al. 2007; Hansen et al. 2004; Hikage et al. 2008; Jeong & Smoot 2007; Larson & Wandelt 2004, 2005; Land & Magueijo 2005; Lew 2008; McEwen et al. 2005, 2006a,b; Magueijo & Medeiros 2004; Medeiros & Contaldi 2006; Monteserin et al. 2007; Mukherjee & Wang 2004; Naselsky et al. 2007; Raeth et al. 2007; Sadegh Movahed et al. 2006; Tojeiro et al. 2006; Vielva et al. 2003; Wiaux et al. 2006; Wiaux et al. 2008; Yadav & Wandelt 2007. Deviations from Gaussianity have been detected in many of these works. Although the WMAP5 data are consistent with previous releases, the modelling of beams is improved considerably, new masks are defined and a further two-years of observations mean that the WMAP5 data can provide reliable confirmation of previous non-Gaussianity analyses.

In this article we focus on the detection of non-Gaussianity that we made previously in the WMAP1 and WMAP3 data (McEwen et al. 2005, 2006a). The Kp0 mask provided for previous WMAP releases and used in our Gaussianity analyses was constructed from the K-band WMAP observations, which contain CMB and foreground emission. Consequently, the application of this mask may introduce negative skewness in the distribution of the CMB (Komatsu et al. 2008). Since our previous detections of non-Gaussianity were observations of negative skewness in wavelet coefficients computed from WMAP data masked in this manner, it is prudent to readdress our analysis in light of the new WMAP data and masks. The remainder of this letter is organised as follows. In Sec. 2 we discuss the WMAP5 map considered and present the results of the non-Gaussianity analysis. Concluding remarks are made in Sec. 3.

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2 NON-GAUSSIANITY ANALYSIS AND RESULTS

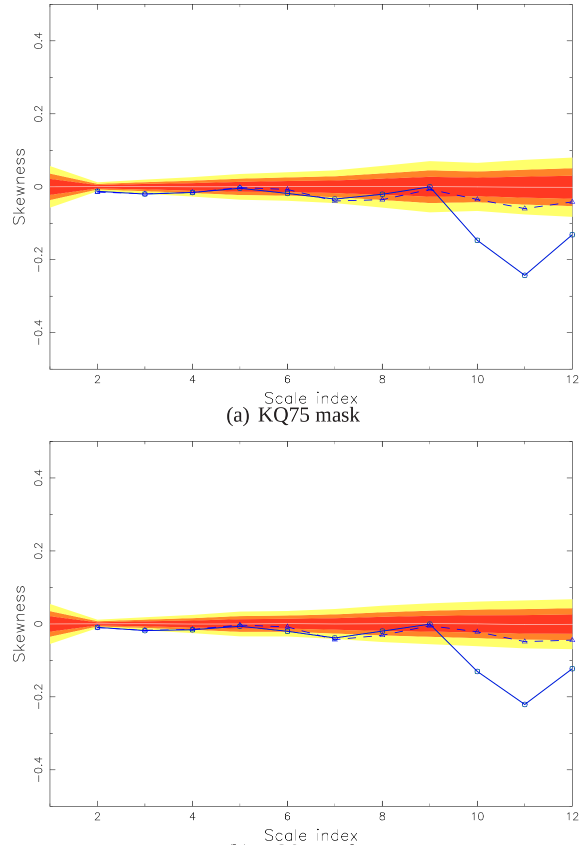
We repeat our non-Gaussianity analysis performed previously on the WMAP1 and WMAP3 data (McEwen et al. 2005, 2006a), focusing on the most significant detection of non-Gaussianity made in the skewness of real Morlet wavelet coefficients. A detailed description of the analysis procedure is presented in McEwen et al. (2005) and a brief overview is also given in McEwen et al. (2006a). Consequently, we do not review the method in detail here but merely comment that it involves a Monte Carlo analysis of real Morlet wavelet coefficients of the data. Twelve scales a_i spaced equally between $50'$ and $600'$ are considered. Furthermore, the real Morlet wavelet analysis probes directional structure in the data and we examine five wavelet azimuthal orientations spaced equally in the domain $[0, \pi)$. The directional analysis is facilitated by our fast directional continuous spherical wavelet transform code (McEwen et al. 2007), which is based on the fast spherical convolution developed by Wandelt & Górski (2001).

We consider the signal-to-noise ratio enhanced co-added map constructed from the WMAP5 data (see Komatsu et al. (2003), McEwen et al. (2005) for descriptions of the co-added map construction procedure). Each simulated map used in the Monte Carlo simulations is constructed in an analogous manner to the co-added map constructed from the data. A Gaussian CMB realisation is simulated from the theoretical Λ Cold Dark Matter (ΛCDM) power spectrum fitted by the WMAP team (Dunkley et al. 2008). Measurements made by the various receivers are then simulated by convolving with realistic beams and adding anisotropic noise for each receiver, where the beams and noise properties used correspond to WMAP5 observations. The simulated observations for each receiver are then combined to give a co-added map. In this analysis we use the new KQ75 and KQ85 masks, rather than the Kp0 mask used in our previous analyses. The construction of these new masks is discussed by Gold et al. (2008). The KQ75 mask is the more conservative of the two new masks and is recommended for Gaussianity analyses (Komatsu et al. 2008). Nevertheless, we consider both masks since these are the changes in the WMAP5 data that are most likely to affect the results of our analysis.

The skewness of the real Morlet wavelet coefficients of the co-added WMAP5 map are displayed in Fig. 1, with confidence intervals constructed from 1000 Monte Carlo simulations consistent with the WMAP5 observations also shown. Only the plot corresponding to the orientation of the maximum deviation from Gaussianity is shown. The non-Gaussian signal present in previous releases of the WMAP data is clearly present in the WMAP5 data for both choices of mask. In particular, the large deviation on scale $a_{11} = 550'$ and orientation $\gamma = 72°$ remains.

Next we consider in more detail the most significant deviation from Gaussianity on scale $a_{11} = 550'$ and orientation $\gamma = 72°$. Fig. 2 shows histograms of this particular statistic constructed from the WMAP5 Monte Carlo simulations for both masks. The skewness value measured from the data is also shown on the plot, with the number of standard deviations each observation deviates from the mean of the appropriate set of simulations. The distribution of this skewness statistic is not significantly altered between simulations analyses with the KQ75 or KQ85 masks. The observed statistics for the data are also similar for both masks.

To quantify the statistical significance of the detected deviation from Gaussianity we consider two techniques. The first technique involves comparing the deviation of the skewness statistic computed from the WMAP5 data on scale $a_{11} = 550'$ and orientation $\gamma = 72°$ to all statistics computed from the simulations. This is



(a) KQ75 mask

(b) KQ85 mask

Figure 1. Real Morlet wavelet coefficient skewness statistics ($\gamma = 72°$). Points are plotted for the WMAP5 data (solid, blue, circles), and the WMAP5 data with localised regions removed (dashed, blue, triangles). Confidence regions obtained from 1000 WMAP5 Monte Carlo simulations are shown for 68% (red), 95% (orange) and 99% (yellow) levels, as is the mean (solid white line). Panel (a) shows the statistics computed using the KQ75 mask, whereas panel (b) shows the statistics computing using the KQ85 mask.

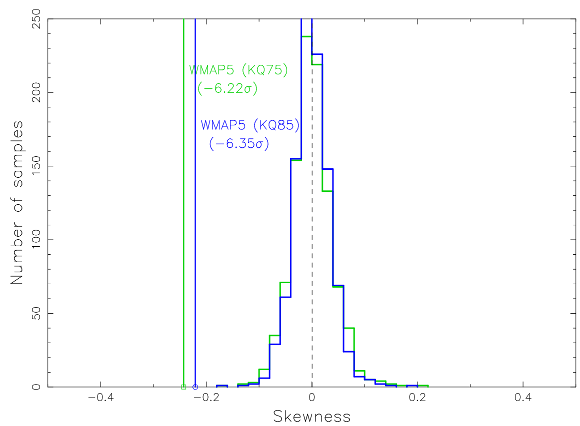


Figure 2. Histograms of real Morlet wavelet coefficient skewness ($a_{11} = 550'$; $\gamma = 72°$) obtained from 1000 WMAP5 Monte Carlo simulations. Histograms are plotted for statistics computed from the simulations using the KQ75 (green) and KQ85 (blue) masks. The observed statistics for the WMAP5 data with the KQ75 and KQ85 masks maps are shown by the green and blue lines respectively. The number of standard deviations these observations deviate from the mean of the appropriate set of simulations is also displayed.

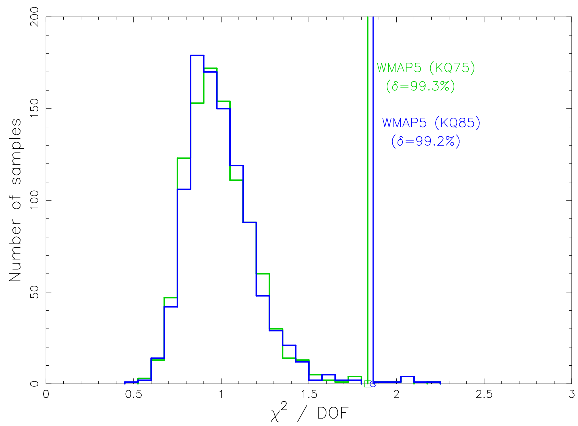
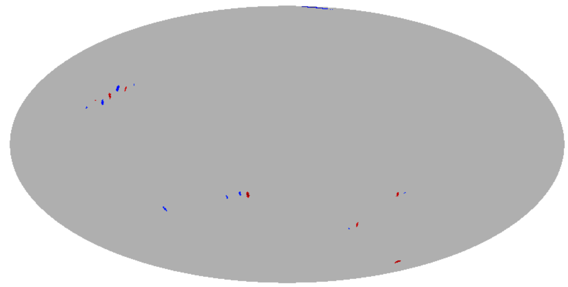
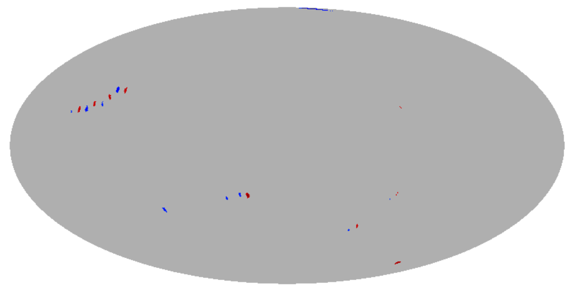


Figure 3. Histograms of normalised χ^2 test statistics computed from real Morlet wavelet coefficient statistics obtained from 1000 WMAP5 Monte Carlo simulations. Histograms are plotted for statistics computed from the simulations using the KQ75 (green) and KQ85 (blue) masks. The χ^2 value for the WMAP5 data with the KQ75 and KQ85 masked maps are shown by the green and blue lines respectively. The significance of these observations, computed from the appropriate set of simulations, is also displayed.



(a) KQ75 mask



(b) KQ85 mask

Figure 4. Real Morlet wavelet thresholded spherical wavelet coefficient maps ($a_{11} = 550'$; $\gamma = 72°$). To localise most likely deviations from Gaussianity on the sky, the original wavelet coefficient map is thresholded so that only those coefficients above 3σ (in absolute value) remain. All sky maps are illustrated in Galactic coordinates, with the Galactic centre in the middle.

a very conservative means of constructing significance levels. The second technique involves performing a χ^2 test. The χ^2 value computed from the WMAP5 data is compared to χ^2 statistics computed from the simulations. In both of these tests we relate the observation to all test statistics computed originally, *i.e.* to both skewness and kurtosis statistics. For a more thorough description of these techniques see McEwen et al. (2005). Using the first technique, the significance of the detection of non-Gaussianity in the WMAP5 is made at $99.2 \pm 0.3\%$ and $99.1 \pm 0.3\%$ using the KQ75 and KQ85 masks respectively. The distribution of χ^2 values obtained from the Monte Carlo simulations is shown in Fig. 3. The χ^2 value obtained for the data is also shown on the plot. Again, the distribution and value observed in the data is not altered significantly when using the different masks. Computing the significance of the detection of non-Gaussianity directly from the χ^2 distributions and observations, the significance of the detection in the WMAP5 data is made at $99.3 \pm 0.3\%$ and $99.2 \pm 0.3\%$ using the KQ75 and KQ85 masks respectively. Using both of the techniques outlined above the detection of non-Gaussianity made in the WMAP5 data is made at a slightly higher significance than in previous releases of the data. Nevertheless, the same non-Gaussian signal appears to be present.

The wavelet analysis allows one to localise those regions on the sky that contribute most significantly to deviations from Gaussianity (McEwen et al. 2005). In Fig. 4 we plot the thresholded wavelet coefficients corresponding to the most significant detection of non-Gaussianity made on scale $a_{11} = 550'$ and orientation $\gamma = 72°$.[1] These localised regions match the localised regions detected in the WMAP1 and WMAP3 data closely. When excluding localised regions from the initial analysis, the highly significant non-Gaussian signals present previously are eliminated (see Fig. 1).

In our previous non-Gaussianity analyses we concluded that noise was not atypical in the localised regions detected (McEwen et al. 2005). Moreover, we also concluded that foregrounds and systematics were not the likely source of the detected non-Gaussianity (McEwen et al. 2006b). The localised regions detected in the WMAP5 data have not changed markedly to those detected previously and foregrounds and systematics are treated more thoroughly, hence we do not expect these findings to alter in the WMAP5 data.

[1] We make corresponding localised region masks available publicly from `http://www.mrao.cam.ac.uk/~jdm57/` so that other researchers may determine whether these regions are responsible for detections of non-Gaussianity made with other analysis techniques.

3 CONCLUSIONS

In this work we have repeated our non-Gaussianity analysis on the WMAP5 data. The non-Gaussian signal detected previously remains present in the WMAP5 data. The possible introduction of negative skewness in the WMAP data by the application of the Kp0 mask (Komatsu et al. 2008) appears not to be responsible for our non-Gaussian signal. Non-Gaussianity is detected at significance levels of $99.2 \pm 0.3\%$ and $99.1 \pm 0.3\%$ using the KQ75 and KQ85 masks respectively, when using our conservative method for constructing significance measures. Using our second method, which is based on a χ^2 analysis, the significance of the detection is made at $99.3 \pm 0.3\%$ and $99.2 \pm 0.3\%$ using the KQ75 and KQ85 masks respectively. These detections of deviations from Gaussianity are made at a slightly higher significance in the WMAP5 data than in previous releases. We have no intuitive explanation for this marginal rise in significance. The most likely sources of non-Gaussianity that were localised on the sky in the WMAP5 data match those regions detected from previous releases of the data reasonable closely (and are made available publicly).

It is interesting to note that the highly significant detection of primordial non-Gaussianity made with the bispectrum by Yadav & Wandelt (2007) is sensitive to skewness, which is also the type of non-Gaussianity detected with our real Morlet wavelet analysis. To test whether these two analyses detect the same source

of non-Gaussianity, one could remove the localised regions that we detect and repeat the analysis performed by Yadav & Wandelt (2007) to see if their detection of non-Gaussianity remains. This analysis is currently being performed by Yadav & Wandelt (private communication).

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